Supernova Neutrino Detection Efficiencies In DUNE

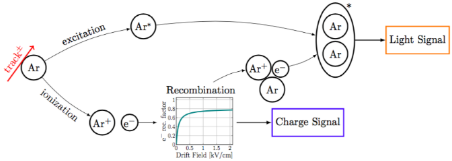
Logan Clutch Jackson Rice

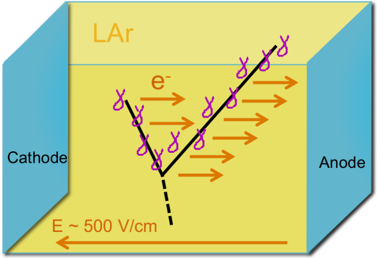
Northern Illinois University, DeKalb, Illinois, USA

June 19, 2018

Charge and Light Signals
In Liquid Argon Time Projection Chambers (LArTPCs)

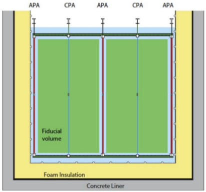
- Charged particles will ionize liquid argon producing charge tracks and light flashes.
- e^- are drifted towards charge collection wires.
- γ's are produced isotropically due to eximer dexitations
  - Two deexcitation channels (prompt light: 7 *ns*; late light: 1.3 μs)
  - Both channels produce 128 +/- 5 *nm* scintillation light

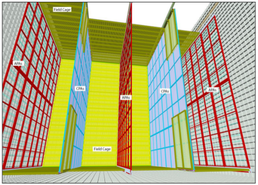


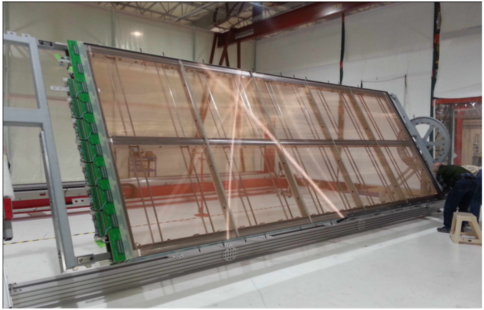


Single Phase Far Detector

DUNE SP FD



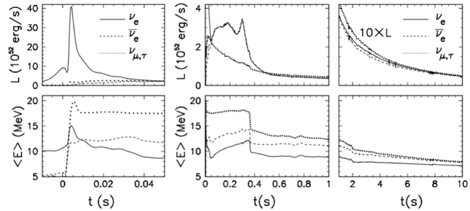


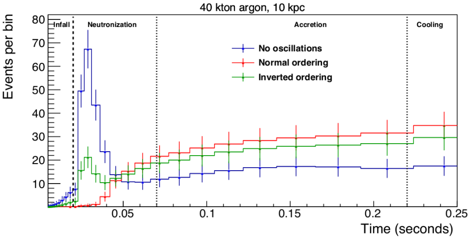


- DUNE SP FD will have alternating anode plane assemblies and cathode plane assemblies
  - CPAs biased to -1.8 kV
  - APAs contain charge induction and collection wires.
  - APAs also contain 10 slots for the photon detection system (PDS).
- 3.6 x 4 drift distances wide 3m x 2 APA's tall and 2.3 m x 25 APA's along the beam direction

Supernova Physics Potential

Lots of interesting physics depends on timing resolution!



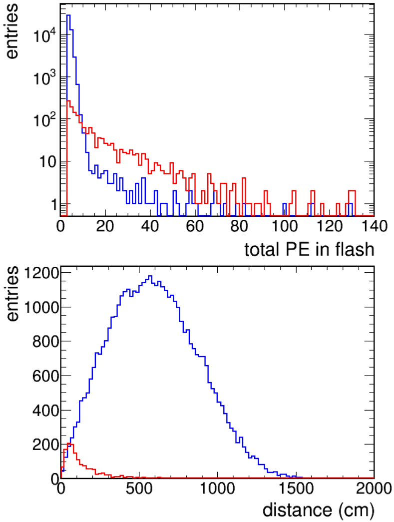


- TOP: Luminosity and energy of ν_e, $\bar{\nu}_e$ and ν_x in a SN
- BOTTOM: Signal ν_e interactions in DUNE depends on mass hierarchy.
- Time evolution of SN neutrinos may be subject to unique effects.
  - Hydrodynamic effects (SASI)
  - Extreme MSW effects
  - Final state of star

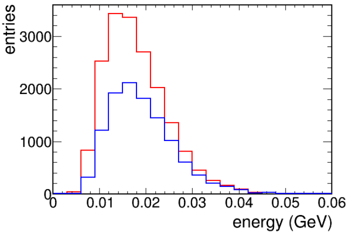
Flash Matching

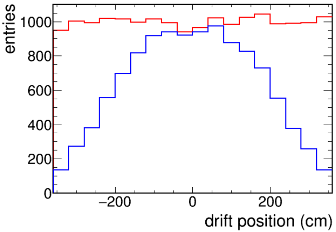
- The charge collection system (TPC) has excellent spatial resolution parallel to the APA plane.
- This information can be combined with the photon detection system (PDS) to gain resolution in time and perpendicular to the APA plane.
- In order to utilize both systems, a reconstructed "flash" seen by the PDS with the reconstructed "tracks" seen by the TPC.
- The challenge is that there is a lot of light activity associated with trace radiologicals present in the drift volume, surrounding rock, and detector system itself.
- The following studies use 3.6 ms long events with radiological backgrounds simulated continuously. There is a single supernova neutrino signal simulated in the middle of the event with the MARLEY generator.

Flash Matching



- Supernova signals on average have larger numbers of photoelectrons (pe) than radiological background signals.
- Define distance as the distance from the position of a flash to the position of the the track vertex
  - Supernova flashes will always be close to their associated flash. This is limited by the spatial resolution of the PDS
  - Radiological flashes will be distributed all over the detector.



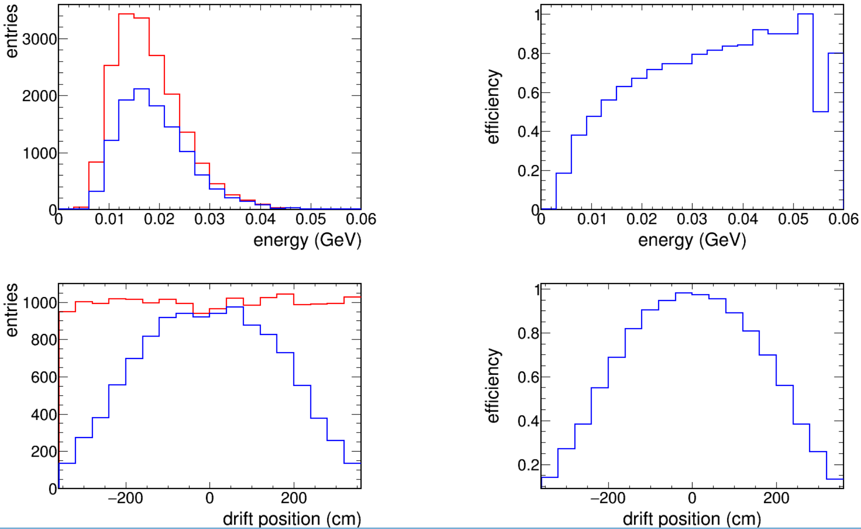


1. Only consider flashes within 240 cm of the true interaction point in the yz plane.
2. Choose the flash with the highest pe.

- These two simple criteria correctly selects a supernova flash from a few dozen background flashes a majority of the time.
- MCTruth spectrum and correctly matched flashes.
- Most effective for interactions
  - With high energy
  - Nearby the APA

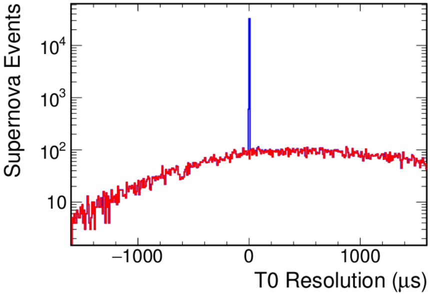
Flash Matching Efficiency

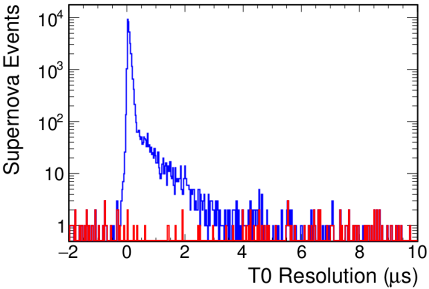
Efficiency = (matched events / total events)



Time Resolution

- When a flash is chosen correctly, the timing is correct within a few hundred nanoseconds
- There is a tail of a few μs which corresponds to the “late light”
- When a flash is chosen incorrectly, there is no time resolution.



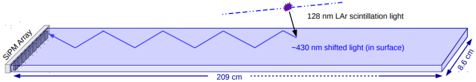


Possible Improvements

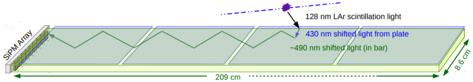
- Improve flash matching
  - Definitely possible
  - Precise optimization will depend on the final flash reconstruction and the final design of the PDS
- Improve flash reconstruction
  - Probably possible
  - Precise optimization will depend on the final design of the PDS
- **Improve PDS**
  - **Definitely possible**
  - **An area of active R&D work.**
  - **☺More light collection = more pe in supernova flashes**
  - **☹More light collection = more background flashes with more pe**

Effective Areas
Values for Possible Designs

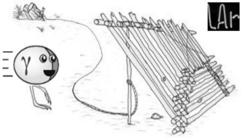
- Effective Area = (Ave. prob. of a photon reaching the detector surface to be recorded) x (Total area)
  - Dip-Coated Designs in protoDUNE: 3.84 cm^2



  - Double-Shifted Designs in protoDUNE 4.1 cm^2

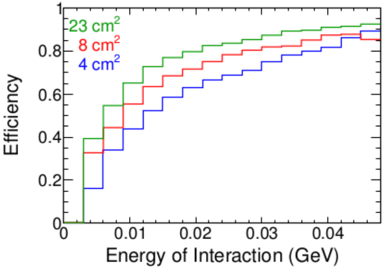


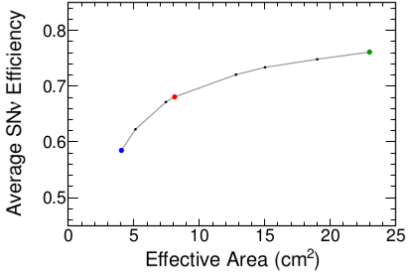
  - Various Arapuca Designs: 5.12 cm^2, 12.80 cm^2, 23 cm^2

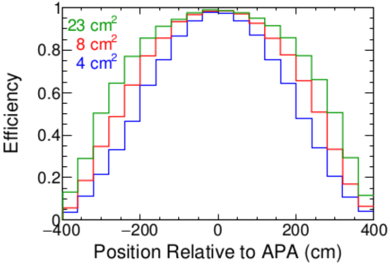


Effective Areas

and Their Flash Matching Efficiencies







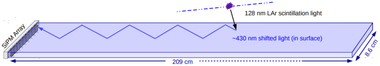
- High EA = overall better efficiency.
- High EA = better spatial and energy uniformity.
- Improvements begin to plateau at high EA.

Conclusions

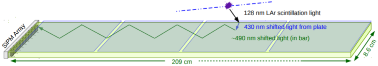
- The impressive sensitivity of the DUNE far detector make it sensitive to supernova neutrino signals (as well as many trace radiological backgrounds).
- The most meaningful analyses of supernova events require matching light and charge signals together.
- Correctly matched photon signals offer excellent timing resolution.
- A simple algorithm matches signals correctly a majority of the time.
- Both the photon detection system and reconstruction process may be significantly improved.
- More effective photodetectors improve flash matching efficiency with a diminishing returns.

Thank You!

- Dip-Coated Design



  - Acrylic light guide with coating to shift wavelengths from 128 nm to 430 nm
  - Total internal refraction guides light to the silicon photomultipliers
  - 209 cm x 8 cm
- Double-Shifted Design



  - Plates attached to the surface shift the 128 nm light
  - Light guide made of scintillating plastic
  - 209 cm x 8 cm
- ARAPUCA Designs
  - Dichroic filter is transparent to 128 nm but reflective to 430 nm light
  - Add a wavelength shifter behind dichroic filter to trap light
  - 10 cm x 8 cm

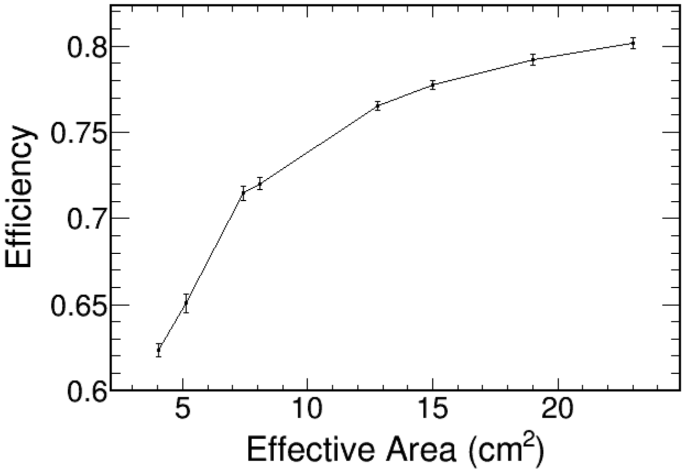
Photon Detection System

Critical To Reconstructing SN Signals

- Neutrino interactions associated with the beam will occur with precise timing (T0).
- Neutrino interactions associated with supernovae may occur at any time.
  - It can take a few milliseconds for charge from the far edge of the drift volume to be collected in the wires.
  - Space charge effects in the drift volume can affect energy reconstruction.
  - The photon detection system will can provide T0. By subtracting this time from the time of the of the charge collection signal, the position in the drift direction can be calculated. This information informs energy reconstruction.

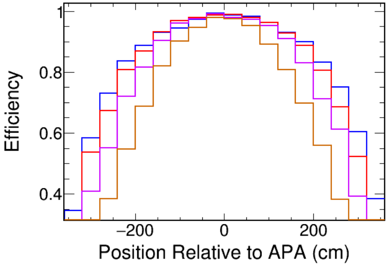
Flash Matching Efficiency

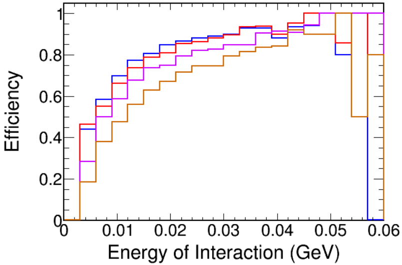
= (# Correctly Match Flashes) / (# Simulated Events)



Flash Matching Efficiency
= (# Correctly Match Flashes) / (# Simulated Events)

23 cm^2 15.02 cm^2 8.11 cm^2 4.05 cm^2



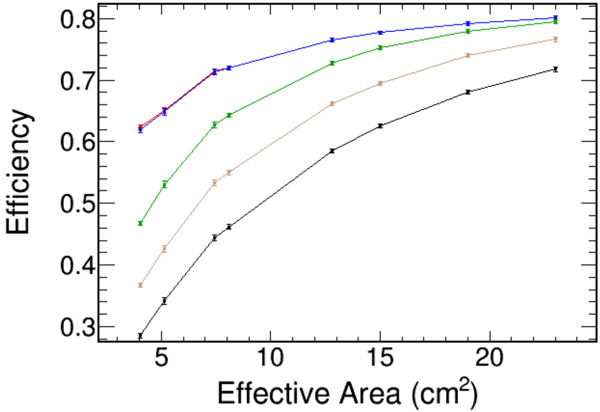


Assumptions

- We've made several assumptions. We assume...
  ... that we know position in the yz plane
  ... that all designs have the same geometry
  ... we can always see 1 pe signals
- The last assumption is particularly problematic. As effective area increases, there will be more flash events and more data to be read out by the electronics.
- What if we assume that we only read out optical information if one of the detectors is above some PE threshold?

Flash Matching Efficiency
= (# Correctly Match Flashes) / (# Simulated Events)

no threshold >1.5 PE >2.5 PE >3.5 PE >4.5 PE

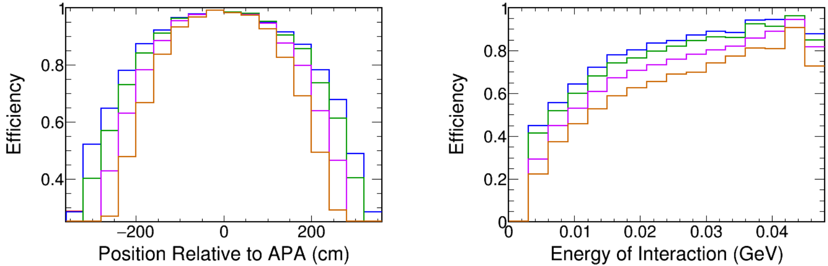


Flash Matching Efficiency
= (# Correctly Match Flashes) / (# Simulated Events)

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

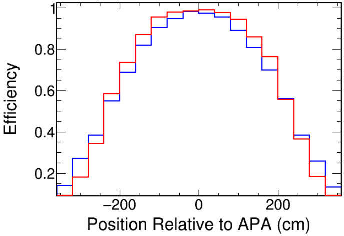
- These histograms correspond to the specific effective area = 12.80 cm^2.

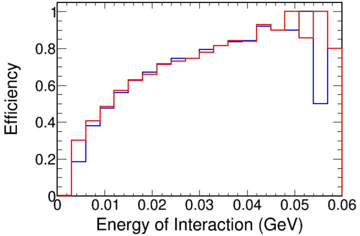
no threshold $>$1.5 PE $>$2.5 PE $>$3.5 PE $>$4.5 PE



Flash Matching Efficiency
= (# Correctly Match Flashes) / (# Simulated Events)

- These histograms correspond to the specific flashmatch efficiency of around 62.4%.
- The 4.05 cm^2 design with no threshold yields 62.3% efficiency.
- The 15.02 cm^2 design with a 4.5 PE threshold yields 62.5% efficiency.





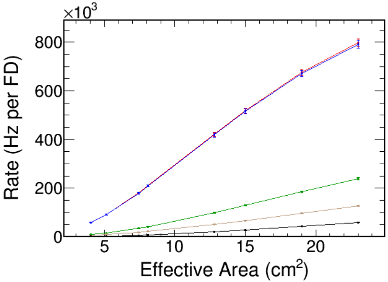
- There is a decrease in spatial uniformity when large thresholds are applied.

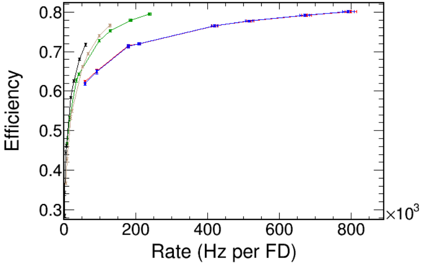
Trigger Rate
How Often Is There a Flash Above a Threshold?

- The motivation to use a threshold is to reduce the rate at which we read in data.
- How much of a reduction can we actually get?
- Define a trigger rate as the rate at which background flashes have at least one optical detector above the threshold PE.
- In this study the marley + radiological data files were used, but the rate was calculated from time windows away from the the sn interactions.

Trigger Rate,
Effective Area, and Efficiency

nothreshold   >1.5 PE   >2.5 PE   >3.5 PE   >4.5 PE



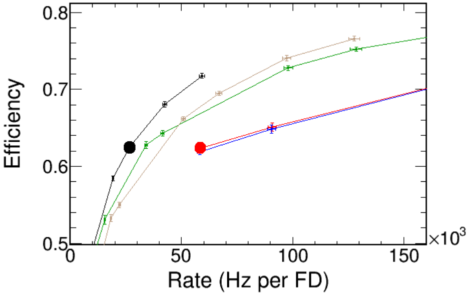


- The rate was calculated in the 1x2x6 simulation and multiplied by 8.333.
- The trigger rate should be related to detector volume.
- 1x2x6 volume = 2x2x6 = 24 volume units.
- Full detector = 4x2x25 = 200 volume units.

Efficiency and Trigger Rate

zoomed

- **4.05 cm^2 detectors and no threshold (Rate = 58.3 kHz)**
- **15.02 cm^2 detectors with a 4.5 PE threshold (Rate = 26.7 kHz)**
- As discussed earlier, both of these schemes have flash matching efficiencies of about 63.4%.

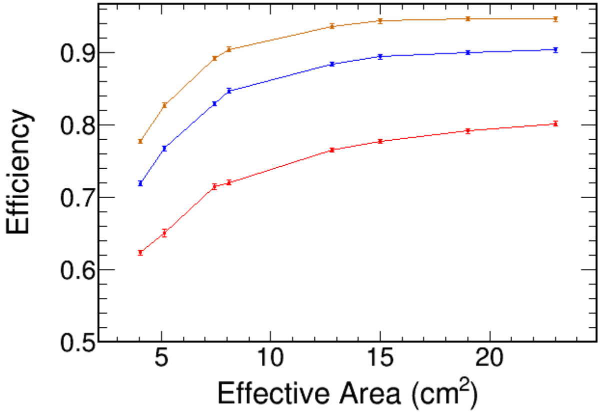


Conclusion

- Two simple criterea select the supernova flashes from background flashes 60-80% of the time. This could be improved.
- When flashes are correctly matched, we have excellent timing resolution.
- More efficient detectors impove flash matching capabilities, but improvements are less than linear.
- More efficient detectors have more noise related to radiological backgrounds.
- A single, simple cut greatly reduces this noise. This could be improved.
- It would be interesting to know how much data per trigger should be read out. Combining this with the trigger rate would give us a data rate value in MB/s.

Reconstruction Efficiency

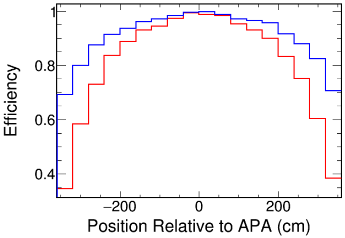
reconstruction efficiency for purity > 0 reco eff for purity > 0.5
selection eff

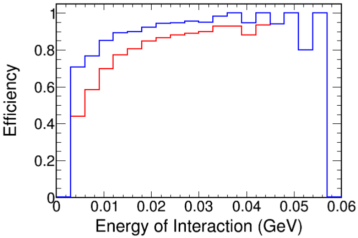


Reconstruction Efficiency

reconstruction efficiency for purity > 0.5 selection efficiency

- For effective areas in the high teens, flash reconstruction efficiencies no longer increase with effective areas. Selection efficiency rises slowly.
- Below are spectrums for 23.00 cm^2. There is still significant nonuniformity in reconstruction and flash selection efficiency.





Bibliography

[1] T. D. Collaboration, "The Single-Phase ProtoDUNE Technical Design Report," Tech. Rep., Jul. 2017.